Experimental Study of High Field Limits of RF Cavities

Classification (subsystem)
High gradient rf systems

Personnel and Institution(s) requesting funding
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Project Overview
We want to understand how the maximum fields in high gradient systems depend on the surface material and explore the improvements that modifications can bring.

Although high electric fields have been used in DC and RF applications for many years, up to now there has been no fundamental agreement on the cause of breakdown in these systems [1]. Recently, a group from the Muon Collaboration doing accelerator R&D, computer modelers at Argonne, and materials scientists using Atom Probe Field Ion Microscopy (APFIM) at Northwestern, have had success understanding the process in terms of high mechanical stresses at local field emitters in cavities. We have published this work in Phys Rev STAB, Nuclear Instruments and Methods, and many accelerator conference papers over the 18 months [2][3][4]. The most interesting discovery in this work has been that the pre-breakdown environment we measured in rf cavities, (0.1 µm asperities, ∼10 GV/m electric fields) has been used in material science for years, for precisely the sort of measurements we would like to make [5]. This technology has been aggressively developed and has had recent breakthroughs such as the Local Electrode Atom Probe (LEAP) microscope [6].

Our model predicts that high voltage systems will break down when the mechanical stress produced by the local electric field exceeds the tensile strength of the surface material. This model seems to agree with all the good data we can find on copper rf structures. The figure shows how data on the maximum gradients produced in CLIC, NLC, KEK, the Muon Collaboration and old linacs compare with superconducting rf systems optimized for the ILC [2][7]. (CLIC data tolerated higher breakdown rates, and claim to be consistent with our argument [8].) The model strongly argues that breakdown events are the result of fragments or clusters breaking off of the surface and rapidly being ionized in the electron beams from the field emitter. Within the active volume, the power involved in these beams is comparable to nuclear weapons. This model is also generally in agreement with the experience with APFIM samples at the high fields used. Tiny APFIM samples operate at fields about 5 times higher than the local E field limit we postulate, but they also frequently fail, however there has been no systematic study of these failure modes.

Although the limits of superconducting systems like the ILC may be dominated by magnetic field effects, this model applies directly to failures due to field emission, it describes high
Figure 1: High field operating conditions for accelerator structures, and the trigger mechanism we propose compared to 50 - 100 year old DC data. Local tensile stresses and power densities can be very high.

power processing, and this work should be essential to the development of large quantities of superconducting surfaces running at the highest possible gradients.

The study of high fields proposed here is not an isolated effort. This work will involve a collaboration with the Muon Collaboration who are optimizing the surfaces in a working cavities at 805 and 201 MHz, with significant interests in converging on practical methods to operate at high accelerating fields in high magnetic fields. We will also be working with modeling experts at Argonne who are interested in showing how the basic mechanisms of breakdown work. A third interaction will be with superconducting rf programs at ANL and FNAL, who want metallurgical information on the surface configuration of superconductors, i.e. how the oxides, impurities, and supercurrents coexist in the top 50 microns of a superconductor.

The lack of basic knowledge of how the defining fields of the machine were produced was partially responsible for the catastrophes of ISABELLE (which could not produce magnets which matched the prototype), the SSC (which did not have the required data on conductor placement tolerances / good field region), and the NLC (which was plagued by breakdown events from then unknown causes). (The Tevatron, it seems, was sold as an "Energy Saver" and not as an energy frontier machine.) We believe an understanding of the basic processes of breakdown and the structure and influence of the conductor surface is essential to the credibility of the ILC design.

At the present time, the best experimental data for the high field breakdown thresholds of different materials is a Masters Thesis from Berkeley, in 1964, which was not done according to modern standards[9]. The environment of a APFIM permits this and other experiments under highly controlled conditions, over a wide range of parameters, which have never been possible for rf systems.

**Broader Impact**

We believe this work is of general interest to a very wide community. We had contacted
Figure 2: Early data (1900 -1905) on surface breakdown from Refs [10-11] showing \(\sim 150\) MV/m breakdown thresholds, and comparative power densities for astronomical and terrestrial power sources showing field emitted electrons generate very high power densities in small volumes.

the Argonne Office of Public Affairs and talked with them about issuing a Press Release three months ago, saying that we had a solution to one of the longest lasting problems in experimental physics, i.e. high voltage vacuum breakdown. We were diverted from this by the pressures of events, but we intend to get back to them as soon as things settle down a little. There is almost no interaction between "Big Science" and the general public on practical issues, and the connection we have made between very old data, common phenomena and very exotic physics should be interesting to a wide community. We think this work should be in the New York Times.

Breakdown at surfaces was discovered by Earhart and Michelson, at Chicago, in 1900 [10]. While checking the new "electron" theory of gas breakdown at small distances, they discovered that there were two mechanisms present, at large distances gas breakdown dominated, and at small distances breakdown of the surface was correctly identified as the mechanism. The break point where the two mechanisms met, at atmospheric pressure, occurs at about 300 V. This was confirmed 5 years later by Hobbs and Millikan [11], and is consistent with modern data on vacuum breakdown. Until our work, no theoretical understanding of this process developed over the last 100 years, although many papers have been written[1]. It is interesting to note that all consumer power switching takes place below 300 V, thus when switching on power in the home or lab, the initial contact is due to breakdown of a surface. This mechanism is thus accessible to everyone.

Another interesting feature of this mechanism is that the power densities involved are enormous. The numbers can be obtained from the values we measured for field emitted currents, electric field, the emitter dimensions, and volume for transferring electromagnetic field energy into electron kinetic energy[2]. Combining these gives, \((10 \text{ GV/m})(10^{-7} \text{ m})(1 \text{ mA})/(10^{-7} \text{ m})^3 = 10^{21} \text{ W/m}^3\), a value that seems to be greater than all other natural effects, except perhaps Gamma Ray Bursters (GRB’s) [12]. The power density is comparable to nuclear weapons. Michelson and Millikan noticed the "hot sparks" in 1905, bought a vacuum pump, (which they didn’t have), and invented vacuum ultraviolet spectroscopy. Both moved on, and did not look in detail at the mechanisms involved.
Combining these two ideas, however, one can conclude that: 1) this mechanism produces perhaps the highest power density commonly found in nature, and, 2) it is accessible to anyone with a wall switch or an electric light, and is used many times a day by everyone. These two facts should make this work almost irresistible to a wide spectrum of introductory physics courses, news media and science fair experiments. We believe it is very important for High Energy Physics to show that it can say interesting things to the general population. We want to experimentally verify the details first, however.

Vacuum breakdown affects many disciplines and technologies. Although there have been a variety of ways to work around this problem, a fundamental understanding of the mechanisms should be helpful, interesting and productive to a very wide community. In APFIM, like many branches of science and technology that use high voltages in vacuum, these mechanisms can also be an irritation. Although there are usually ways to work around problems, basic understanding of the problem is long overdue.

We have given a large number of talks on this subject in the last two years: FNAL (3 Acc. Sci. and Tech. Seminars), SLAC (Linear Collider Design Group), PAC03, Our High Gradient rf Workshop at Argonne, (3 talks), Northwestern (Mat. Sci. and Eng. Seminar), Argonne HEP (2 lunch seminars, 1 accelerator seminar), Univ of Chicago (Enrico Fermi Inst. Seminar), Int. Vac. Nanoelectronics Conf. EPAC04 and LINAC04.

The Northwestern University Center for Atom-Probe Tomography (NUCAPT) has an existing outreach program to involve women and legal minorities in the LEAP microscope work. There are many connections with local colleges (Harold Washington College) and with Evanston Township High School (ETHS).

Results of Prior Research

This work has grown from the study of cavities in a magnetic field done for the Muon Collaboration, to understand how cavities operated in a magnetic field and near sensitive single particle detectors. X rays were presumed to be a problem and in fact they have been. Prior funding for the breakdown studies has come from an Argonne LDRD.

We think we have developed a model of breakdown that explains the phenomenon in almost all environments, which can make quantitative, easily testable predictions. The data required for these predictions are also very easy to acquire, requiring only a radiation monitor and some way of measuring the relative electric field in the cavity at two values. We have tested these models in a variety of environments and published the results [2]. We are beginning to trust them.

While there has been extensive study of the time development of breakdown events from the first small local ionization to complete breakdown of a cavity, the trigger for breakdown, and how it was related to the metallurgy of surfaces has received very little attention until now. Our model predicts that the production of clusters and fragments is an essential component of breakdown. This is consistent with experience in Atom Probe Tomography, however there is almost no systematic data on sample failures under the high field environment used in data taking.

Our previous work has been published in three refereed papers and many conference papers. The Muon Collaboration summary of the results of our open cell cavity, an outline of the mechanisms of triggers for rf breakdown and a detailed calculation of the properties of clusters emitted from surfaces at high field. We have mentioned that one of the surprises of this work.
Figure 3: An Atom Probe Field Ion Microscope (APFIM) uses a pulsed voltage to evaporate single atoms from a sample and a microchannel plate plus a delay line detector to determine their position and velocity, enabling reconstruction of the positions of the atoms in the original solid.

was the discovery that Atom Probe Field Ion Microscopes studied the same environment that causes breakdown in rf cavities. Specific technical highlights of this work include:

- Understanding x ray production from rf cavities.[13]
- Identification of mechanical stress as the primary trigger for high field breakdown[2][3].
- Discovery of discontinuities in Voltage vs. time plots in APFIM data that confirm emission of fragments[3]. This is shown in Figure 3.
- Preliminary models of the early development of breakdown triggers in an rf field[3] [14].
- Successful comparison of this model with data from NLC, KEK, IPNS and ISIS linacs[2].
- Modeling of the emission of clusters at high fields[4].
- Identification of other mechanisms, 1) Production of GV/m fields by from interactions between surface current and defects [3]. 2) High stresses produced within emitters when field emission currents interact with high static B fields. These two mechanisms are less common under optimum conditions.
- Hosting an international workshop on High Gradient RF[15][16].
- Constructing a facility for applying and measuring surface properties (coatings) in an APFIM.

The environments where these systems have been tested have been the comparatively dirty, inaccessible and uncontrolled surfaces of rf cavities. While this is good for the understanding rf cavities, it is more interesting and valuable to test the models over a wide variety of materials, temperatures, surface treatments, and mechanical stresses, in a highly controlled environment with excellent instrumentation. This is what we want to do.

Facilities, Equipment and Other Resources
Atom probe tomography is a rapidly advancing field. The recent development of the LEAP microscope has extended the resolution, sensitivity, statistics and graphics of this technology.
Figure 4: Discontinuities in the voltage vs. time (constant erosion rate) plot for an APFIM. During normal operation the voltage in these devices is controlled to maintain a stable evaporation rate, effectively determining a constant surface field. Since $E \sim \frac{V}{r}$, measured voltage is proportional to tip radius ($\sim 50$ nm). Size (in nm) assumes fragments are cubes.

In addition we have constructed a facility to do testing of coatings for the Muon Collaboration. The purpose of these tests is to test and measure coatings that can suppress dark currents in the Muon Ionization Cooling Experiment (MICE).

Recently ANL and the Northwestern University Center for Atom-Probe Tomography (NU-CAPT), directed by Prof. David Seidman have joined forces to understand how the maximum fields in high gradient systems depend on the surface material. The NUCAPT is among the world leaders in the field of three-dimensional atom-probe microscopy, particularly as result of the recent installation of a LEAP microscope, manufactured by Imago Scientific Instruments [6]. Currently only three other LEAP microscopes, with a comparable performance, exist throughout the world. Atomic-probe tomography consists of dissecting a specimen on an atom-by-atom basis, employing pulsed field-evaporation, and determining the chemical identity of each field-evaporated atom by time-of-flight (TOF) mass spectrometry, with single atom identification capability, using a 2D position sensitive delay line detector, which yields the position of each atom in a specimen with sub-nanoscale resolution. Analysis rates of upwards of 72 million atoms/hr have been achieved employing a LEAP microscope at NU[17][18]. The collected data is used to reconstruct a specimen in three-dimensions, where the chemical identity of each atom is known. In addition to the LEAP microscope there is also a pulsed-laser atom-probe (PLAP) microscope, which permits one to dissect a tip atom-by-atom using nanosecond laser pulses produced by a nitrogen laser or pulsed electric fields. The PLAP has a pre-chamber that permits us to deposit different metallic coatings on copper tips or other substrates, under ultrahigh vacuum (UHV) conditions. The collaboration between ANL and NUCAPT will produce spectacular results with lasting impact and strongly advance the understanding of how the maximum fields in high gradient systems depend on the surface material.

An example of the ability of our three-dimensional atom-probe (3DAP) microscope to reconstruct a specimen with subnanometer spatial resolution and chemical identification of individual atoms is shown in Figure 5 (left). This figure shows the nanostructure of an Fe-
Figure 5: LEAP resolution and sensitivity, how it sees samples (note atomic planes and individual atoms). Compare the fragment dimensions in Fig. 3, with the 100 nm tip size to see the magnitude of discontinuities.

Figure 6: Left: 3DAP microscope reconstruction of an Fe-Al-Ni-Cu-2 steel, after austenitizing at 1050°C, quenching, and aging at 823 K for 2 hr. The reconstructed volume is 14x13x27 nm$^3$ and contains 204,000 atoms. The (110) planes, an interplanar spacing of 0.203 nm, are resolved. Right: (a) A 5 at. % Cu isoconcentration surface (red) delineates Cu-rich precipitates in Fe-Al-Ni-Cu-2 steel. (b) The proxigram concentration profile displays a quantitative compositional analysis of the precipitates shown in (a), together with the surrounding matrix.
Cu-Ni-Al-Si-Mn-C ferritic steel, developed to have blast-resistant properties, that had been heat treated to produce a high number density \(6 \times 10^{24} \text{m}^{-3}\) of nanometer diameter (0.5 to 2 nm) copper-rich precipitates\[19\]. The 110 atomic planes are clearly resolved with an inter-planar spacing of 0.203 nm. Also note that individual atoms within the 110 are resolved and their chemical identities obtained. This nanostructure yields excellent mechanical properties: A yield strength of 135 ksi (ca. 945 MPa) and an ultimate tensile strength of 145 ksi (ca. 1015 MPa) are obtained to below -40°C and the ductility is 30%. Figure 5 (right) (a) (next one) exhibits Cu-rich precipitates in the same ferritic steel that are indicated by a 5 at.% Cu isoconcentration surface (red) in the indicated volume of material; note, no atoms are displayed in this representation \[19\]. The so-called proxigram of the different elements in this steel are displayed in Figure 5(b), which yields the concentration profiles as a function of distance from the matrix/precipitate interface; the latter is at 0 nm. This figure shows directly the variations of concentrations of all the elements both within the matrix and the copper-rich precipitate. There is currently no other way to obtain this type of chemical information with the same spatial resolution. The LEAP microscope will be employed to determine the chemical compositions of different coated substrates both before and after they have failed during pulsed field-evaporation with an electric field.

**FY2005 Project Activities and Deliverables**

We are presently funded from Argonne LDRD funds. These funds will allow us to present preliminary data at PAC05 and the Cornell superconducting workshop.

We understand that the behavior of surfaces under high fields depends partially on the top monolayer, (field emission) and partially on the bulk properties (breakdown). With our facilities we will be able to independently vary bulk and surface properties and measure a wide spectrum of behavior due to a wide spectrum of materials properties, preparations and variables such as temperature and exposure to gasses. There are a number of approaches we would like to begin in the first year:

- From the point of view of breakdown studies, the most important data would be the spectrum of failure of samples as a function of applied field. As there is no reliable, systematic data on breakdown thresholds for different materials, it would be desirable to do this with a large sample of materials, under a variety of conditions such as temperature, gas pressure and surface modification techniques. The coatings we would like to apply become one of the important variables here and these must also be studied systematically to determine the bonding of coating with substrate.

- Suppression of field emission. It has been shown that fractions of a monolayer of materials with different work functions will change the field emission by large factors. What is not known is how to apply these materials to real surfaces, and how the surfaces will stick in the presence of oxide layers, gasses and a variety of other real world effects. These can be experimentally checked. The materials with desirable work functions do not obviously bond strongly to the surfaces we would like to use, and it is possible to look at ways to improve this bonding with intermediate layers.

- Study of clusters and fragments. Our breakdown model implies that the emission of clusters and fragments from the surface is an important component of the breakdown trigger. There is a little published data that confirms that these effects exist. We would like to look at ways that an APFIM can be made more sensitive to this phenomena and look systematically for these clusters and fragments. We would also like to look at
LEAP data to see if there is any evidence for cluster and fragment emission as part of sample failure modes.

- Find the constraints on the superconducting rf surface and see if there are ways of modifying the surface, for example with multilayer oxides, which would protect the ILC superconductor from the primary effects of O and H penetration, dust and other contaminants.

At the end of the first year we will have our coating facility operating and we should have presented some very preliminary data at PAC05, and the Cornell superconducting rf workshop in the early summer. At the end of the year we will also have some useful preliminary data from runs for other users on the LEAP microscope which will provide useful information on how to proceed most efficiently.

FY2006 Project Activities and Deliverables

- We will write up the results of these systematic studies. In FY 06 we will primarily do the systematic studies described in the previous section. At the end of this year we should have considerable data to compare with models and guide future experiments.

- We will develop a "best method" for suppressing dark currents and magnetic field induced breakdown events at the end of this period, with extensive documentation. The initial motivation of all this effort to understand the high gradient behavior of metals is to develop practical low frequency cavities for muon cooling. The work has expanded and become more general, but the need for better performance in muon cooling cavities remains. One goal of this work is to develop and justify an optimized coating technology that can be used in a variety of low frequency cavities, such as the 201 MHz structure,
presently under construction and soon to be installed in the Fermilab Muon Test Area. This practical goal should help to keep the studies focused.

**FY2007 Project Activities and Deliverables**

- We will finish final systematic scans, re-take particularly important data and write up the final papers. Since the experimental program we have outlined is all new, the goals in the third year will depend, to some extent, on what we have learned.
- We will modify the breakdown model as needed to accommodate the new data on breakdown. This will incorporate practical effects such as dust, coatings and practical suggestions for simplifying the construction of the ILC superconducting rf system.

**Budget justification:** Northwestern University

The primary costs involved are for support for Dr. Jason Sebastian for 8 months. We have also included some support for time on the LEAP microscope ($250 /day) and misc hardware for modifications to the coating facility and pulsed laser atom probe (PLAP) device. Work in all years will involve both the LEAP device and work with the coating deposition system. While there are no charges for the PLAP, maintenance and modifications must be included in the overall operating expenses.

**Three-year budget, in then-year K$**

**Institution:** Northwestern University

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**References**

[10] R. F. Earhart, Phil Mag. 1 147 (1901)